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In accordance with the terms of the Office of Naval Research Grant No. N00014-93-1-0686, I am sending you the following material:

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| Title:            | Numerical and Symbolic Algorithms for Application Specific Signal Processing |
| Submitted by:     | Prof. Alan V. Oppenheim  |
| Period Covered:   | November 1, 1995 - April 30, 1996  |
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Thank you. Please contact me if you have any questions or comments.

Mary S. Greene  
RLE Financial Assistant, Room 36-437

cc: A.V. Oppenheim (1)  
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OSP 60314

Enclosures

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Semi-Annual Report  
Numerical and Symbolic Algorithms for  
Application Specific Signal Processing

November 1, 1995–April 30, 1996

**Research Organization:** Digital Signal Processing Group  
Research Laboratory of Electronics  
Massachusetts Institute of Technology

**Principal Investigator:** Alan V. Oppenheim  
Distinguished Professor of Electrical Engineering

**Grant Number:** N00014-93-1-0686  
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**Program Manager:** Mr. Clifford Lau

## 1 Introduction

During the period of this grant, our detailed technical accomplishments are reported through journal articles and technical reports. Each of our semi-annual reports will highlight certain technical areas and provide a summary listing of our technical articles related to the project.

## 2 Chaotic Equalization

In the area of chaotic systems, we have continued our work on investigating the use of this class of signals and systems for channel measurements and for spread spectrum communications. Most strategies proposed exploit the self synchronization property of certain chaotic systems. By necessity, synchronization of the receiver requires that the received drive signal be undistorted or that it first be appropriately equalized in amplitude, spectral content and phase. Specifically, it can be anticipated that a realistic transmission channel will introduce a time varying attenuation due to fading, scattering, etc., will modify the spectral characteristics of the transmitted signal due to channel filtering and multipath, and will introduce additive noise. In our work, we have studied the effects of additive noise on synchronization and have developed some specific techniques for estimating and compensating for the effects of the channel on amplitude and spectral content of the synchronizing drive signal. Our specific approach to compensation of channel gain and filtering characteristics is to take advantage of two characteristics of the systems. One is the fact that while in any realization, the specific drive signal is not known, its average power and spectral characteristics are. Consequently, rough compensation can be carried out by normalizing the received drive signal to the known average spectral density. The second characteristic exploits the synchronization property. Specifically, the approximate channel characteristics as estimated through the normalization process are then refined using a gradient search procedure to minimize the average power in the synchronization error.

In our work on soliton systems we have developed a new circuit implementation of a discrete lattice which exhibits soliton behavior, and we have carried out a detailed study of detection and estimation in additive noise of soliton pulses generated by this circuit. The algorithms for parameter estimation and detection all exploit the Toda lattice as a tuned receiver for soliton signals, naturally decoupling the component solitons as they propa-

gate. At high signal to noise ratios, the noise component of the solution to the lattice equations remains low pass and Gaussian and is decoupled from the solitons. This allows for maximum likelihood time-delay estimation and GLRT detection to be performed after preprocessing of the received signal. The resulting estimation algorithms are unbiased and asymptotically approach the Cramer-Rao bounds.

In this and our other work on nonlinear algorithms for signal processing, an essential issue is the mechanisms for accurate simulation, design, and implementation. Because both classes of algorithms described above are inherently analog, the tools used for computer-based design and simulation of these algorithms were HSPICE. Following the simulation, the soliton system was implemented in analog hardware.

### 3 Approximate Processing

The utility of formal methods for the design of systems employing approximate processing techniques depends heavily on the availability of information regarding the tradeoffs obtained between the amount of computation performed by an algorithm and the quality of the results that are obtained. Our recent work on approximate signal processing has involved the performance analysis of various incremental refinement algorithms. In our continued investigation of a large class [1] of incremental refinement algorithms for DFT approximation, we have developed an approach [2] to determining the probability that an output with any specified level of spectral degradation will be obtained when the number of arithmetic operations performed is restricted to a given amount. These results, which are based on probabilistic models of the signals to which the algorithms are applied, can be used to assist in the selection of an appropriate algorithm for a given set of system requirements.

We have also initiated a study of the incremental refinement properties of the FFT. In this work, we have demonstrated [3] that when the FFT is employed for the detection of complex sinusoids of unknown frequency, if one considers halting FFT processing at an intermediate stage of computation and applying ML detection to the intermediate results, the probability of detection improves monotonically with the number of FFT stages completed. By deriving the receiver operating characteristics associated with detection performed after each FFT stage, we have shown that for a wide range of input SNR high probabilities of detection can be obtained without the necessity

of performing all FFT stages. Our analysis allows a system designer to determine the minimum number of FFT stages that must be performed to obtain a desired detection performance for any given input SNR.

Our work on design environments has continued with the addition of new functionality to the IPUS C++ Platform (ICP), a facility for the development of embedded signal processors with sophisticated control requirements. A key element of our recent work, performed in collaboration with RASSP investigators at U.C. Berkeley, has been the incorporation of ICP into the Ptolemy system. The result of this effort, the IPUS Domain for Ptolemy, was demonstrated at the Second RASSP Conference and is scheduled for public release in April 1996 as a part of Ptolemy v0.6. IPUS will be released as an experimental domain, since a number of issues in the integration of ICP and Ptolemy remain to be addressed. For example, we are currently working to develop functionality that allows heterogeneous simulation using the IPUS Domain and in conjunction with the other Ptolemy domains via the Wormhole feature of the Ptolemy kernel.

[1] J. Winograd and S.H. Nawab, "Incremental refinement of DFT and STFT approximations," *IEEE Signal Processing Letters*, Feb. 1995.

[2] J. Winograd and S.H. Nawab, "Probabilistic complexity analysis for a class of approximate DFT algorithms," submitted to *Journal of VLSI Signal Processing*, Oct. 1995.

[3] J. M. Winograd, S.H. Nawab, and A.V. Oppenheim, "FFT-based incremental refinement of suboptimal detection," to appear in *Proceedings of ICASSP '96*, Atlanta, May 1996.

## 4 Distributed Signal Processing

The need for efficient strategies for solving signal processing problems in a distributed manner arises in an increasingly large number of current and future applications. In recent work, we have investigated some of the fundamental issues that arise in solving certain distributed signal processing problems. These particular problems involve optimization of a common objective function given various information-sharing strategies among the constituent processors.

It can be shown that finding optimum solutions for even narrowly defined classes of such problems is generally a computationally very hard (i.e., NP-complete) task. However, imposing additional constraints and structure can facilitate both the identification and implementation of solutions. As

an example, the information that is available to each processor to act on, which is referred to as the information pattern, strongly affects the tractability of the problem and the structure of solutions. In general, the more information that is shared among processors, the better the system performance (and often the more tractable the system design problem). However, sharing large amounts of information requires extensive interprocessor communication, which in turn can require a potentially elaborate network of high bandwidth channels between processors. However, in practice there are often tight constraints on these networks, which strongly limits potential interprocessor communication. Hence, the design of information-sharing strategies for solving distributed signal processing problems involves some fundamental tradeoffs.

In recent work [1], we have developed a new class of information patterns for solving optimization problems in a distributed manner. These periodic sharing information patterns simplify system design while requiring only relatively low-bandwidth interprocessor communication networks. Moreover, we have proven that these new information patterns obey a classic "separation" principle, which means that optimum solutions to the problem have efficient implementations in terms of dynamic programming. We have also developed techniques for bounding the performance of solutions to many of the hardest distributed signal processing problems that take the form of decentralized optimization problems.

As a byproduct of our framework for exploring distributed signal processing algorithms, we are able to obtain some new results on multiuser communication problems. In particular, using our techniques, we have been able to establish that certain protocols for the multiple access broadcast channel are nearly optimal in terms of maximizing throughput [2]. This channel arises in packet-switched multiple-access communication systems where there are many transmitters who must share a single channel to a receiver. The receiver receives a packet successfully only if exactly one transmitter sends a packet; otherwise, the receiver either receives no packet or receives a distorted, undecipherable packet resulting from the collision of two packets. The receiver immediately informs each transmitter whether a packet was received successfully, no packet was received, or a collision of two or more packets occurred. A transmitter may sometimes need to send a packet but may have nothing to send at other times. Each transmitter must make a decision about whether or not to send a packet over the channel based on its own demand for the channel and the common feedback from the receiver. Because the transmitters do not know the demands of all other transmitters,

the problem is a decentralized one.

In future work, we anticipate being able to apply and extend our techniques to a variety of other difficult problems in decentralized signal processing, communications, and control.

[1] J. M. Ooi, S. M. Verbout, J. T. Ludwig, and G. W. Wornell, "A Separation Theorem for Periodic Sharing Information Patterns in Decentralized Control," submitted to IEEE Trans. Automat. Contr., Feb. 1996.

[2] J. M. Ooi and G. W. Wornell, "Decentralized Control of a Multiple Access Broadcast Channel: Performance Bounds," submitted Feb. 1996 to Int. Conf. Dec. Control, (Japan).

## 5 Publications of Work Supported

- [1] J.T. Ludwig, S.H. Nawab, A. Chandrakasan, "Low-Power Digital Filtering Using Approximate Processing," IEEE Journal on Solid State Circuits, vol. 31, no. 3, pp. 395-400, March 1996.
- [2] J. Winograd, J. Ludwig, H. Nawab, A. Chandrakasan, and A. Oppenheim, "Approximate Processing and Incremental Refinement Concepts," Conference Proceedings, RASSP Conference, July 1995, (Washington, D.C.).
- [3] Christoforos N. Hadjicostis, "Fault-Tolerant Computation in Semigroups and Semirings," Conference Proceedings, International Conference on Digital Signal Processing, June 1995, (Limassol, Cyprus).
- [4] J.M. Winograd and S.H. Nawab, "Mixed-radix approach to incremental DFT refinement," Conference Proceedings, SPIE Conference, July 1995, (San Diego, CA).
- [5] A.V. Oppenheim, K.M. Cuomo, R.J. Barron, and A.E. Freedman, "Channel Equalization for Communication with Chaotic Signals," Conference Proceedings, CHAOS Conference, July 1995, (Mystic, CT).
- [6] Steven H. Isabelle, "A Signal Processing Framework for the Analysis and Application of Chaotic Systems," Technical Report 593, MIT Research Laboratory of Electronics, May 1995.
- [7] Christoforos N. Hadjicostis, "Fault-Tolerant Computation in Semigroups and Semirings," Technical Report 594, MIT Research Laboratory of Electronics, May 1995.



- [8] Stanley W. Brown, "A Feasibility Analysis of Single-Sensor Active Noise Cancellation in the Interior of an Automobile," MIT, Department of Electrical Engineering and Computer S.M., June 1995.

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